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Inclination of Inner Radio Spurs and Horizontal Stream of Gas in the Galactic Halo

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Abstract

Inner galactic spurs in the radio continuum located at $l \lesssim 50°$ incline systematically toward the anticenter sides by 20-30°. The spurs are associated with inner spiral arms of H I gas which can be traced up to $|z|=1$-2 kpc above the galactic plane. The z-extensions of H I arms apparently coincide with the continuum spurs in position and inclination.

The systematic inclination suggests the existence of a radial force to push outward the nonthermal emitting region responsible for the spurs. The force may be attributed to dynamical pressure of the order of 10^{-13} dyn cm^{-2} due to an outward horizontal stream of gas in the galactic halo. The velocity of the stream is evaluated as 60-80 km s^{-1} at $|z| \cong 1$ kpc within $\sim$7 kpc of the galactic center.

Key words: Galactic wind; Galaxy; Halo; Radio spurs; Spiral arms.

1. *Introduction*

In the course of our study of galactic spurs in the radio continuum [SOFUE (1973), SOFUE, HAMAJIMA, and FUJIMOTO (1974), and SOFUE (1976); these will be referred to hereafter as Papers I, II, and III, respectively], we found that inner spurs located at $l \lesssim 50°$ incline toward anticenter sides systematically. The inclination occurs at roughly a constant angle of 20-30° to the meridional plane (Paper III).

We have proposed in Paper I that the spurs are tangential views of the nonthermal radio-emitting banks located above and below the spiral arms associated with the galactic shock waves (FUJIMOTO 1966; ROBERTS 1969; ROBERTS and YUAN 1970; TOSA 1973): the galactic shock (GS) hypothesis. In Paper III, we suggested that, if our hypothesis is correct, the inclination may be attributed to some horizontal dynamical pressure on the spurs in the inner region of our Galaxy within $\sim$7 kpc of the center.

In the present paper, we discuss some possible causes of the spur inclination with special reference to a large-scale radial gas flow in the space above the galactic disk (galactic halo). The gas dynamics in the halo seems uncertain from theoretical and observational viewpoints (WOLTJER 1965). We show that the spurs are promising probes for investigating the hydrodynamical state in the galactic halo.

2. *Inner Spurs and Their Systematic Inclinations*

(i) *Continuum Spurs*

A careful inspection of the recent maps of radio continuum background reveals the remarkable fact that the spurs are not perpendicular to the equatorial plane, but are systematically inclined toward increasing longitudes (Paper III).

We have concluded in Paper III that the spurs are systematically inclined from the perpendicular toward anticenter sides at a constant angle of 20-30°. Figure 1 shows the ridge lines collected from the map at 408 MHz of HASLAM et al. (1974) and from the map at 820 MHz of BERKHUIJSEN (1972). Figure 2 shows theoretical ridge lines fitted to spurs which appear on our model contour-map constructed on the basis of the GS hypothesis in Paper III. In figure 3 we plot the observed tilt angles measured from the perpendicular toward the anti-center sides for spurs at l=20-160°. The dashed line shows the theoretical in-

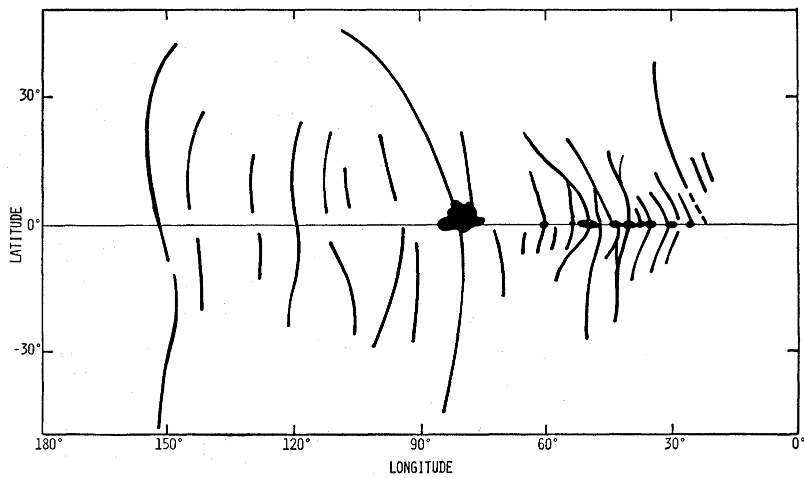

Fig. 1. Spur ridges collected from the maps of radio continuum background at 820 MHz (BERKHUIJSEN 1972) and at 408 MHz (HASLAM et al. 1974). Note a systematic inclination of inner spur ridges toward anticenter sides at $l \leqq 50°$. Dark areas indicate regions where radio brightness attains a maximum in the galactic plane.

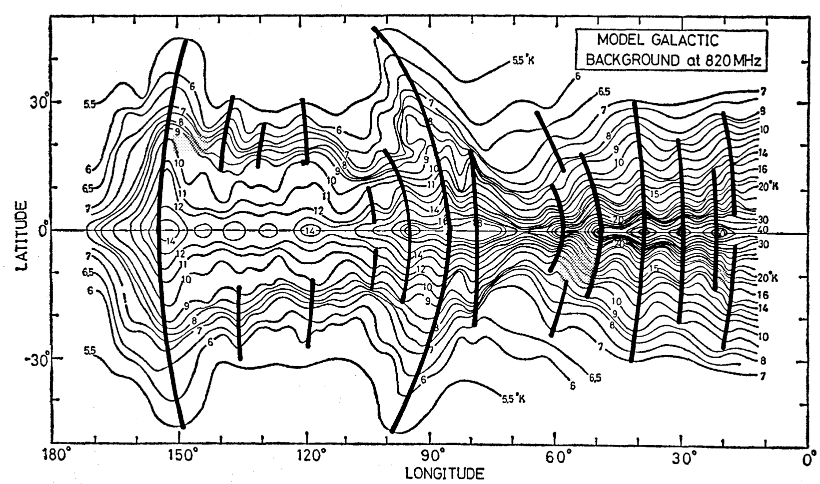

Fig. 2. Theoretical contour map of background at 820 MHz constructed on the basis of the GS hypothesis (SOFUE 1976), and ridge lines fitted to the model spurs.

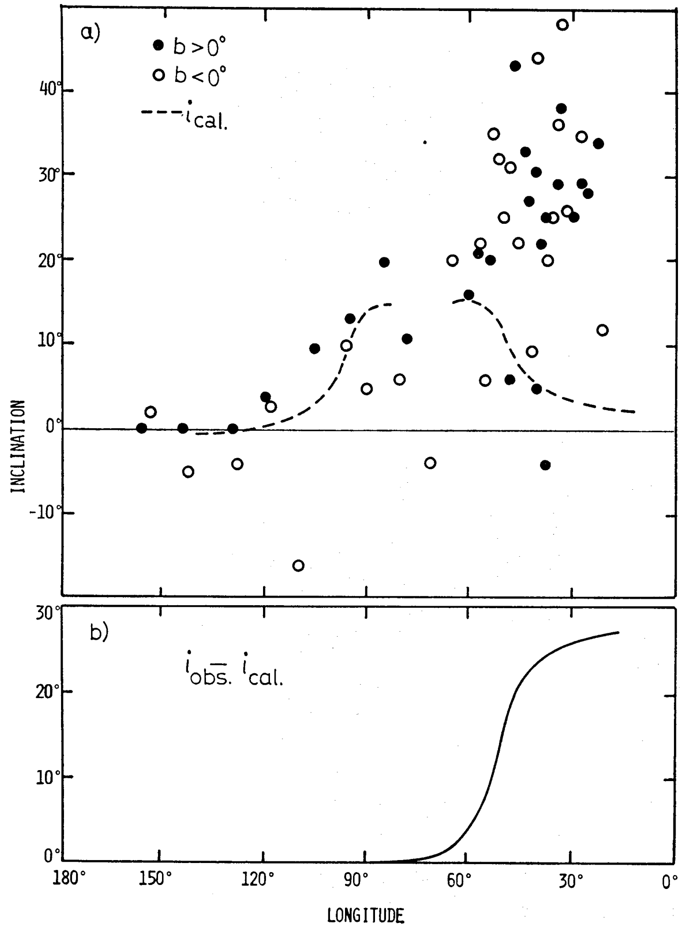

Fig. 3. (a) Inclination angles i of the observed spurs from the perpendicular as read from figure 1 and from the original map of Haslam et al. (1974) at 408 MHz plotted against the longitude. The dashed line indicates inclination of the model spur in figure 2. (b) Difference between the observed and theoretical inclinations. It increases steeply around $l=50°$ as the longitude decreases.

clination of the model spurs when the nonthermal banks responsible for the spurs are assumed to emerge vertically from the galactic plane. Also indicated is the difference between the observed and calculated inclinations.

From these figures, we find that the difference between the theoretical and the observed inclinations increases steeply around $l=50°$ as the longitude decreases. This fact implies that the radio-emitting regions responsible for the spurs are not perpendicular to the galactic plane, but systematically inclined in the region of $l \leqq 50°$. On the other hand, at $l \geqq 60°$, the inclination is well reproduced only from the geometrical effect of the model spurs in Paper III. If we stand on the GS hypothesis, we may conclude that the nonthermal banks are tilted toward anticenter sides within $\varpi=7$ kpc, but that there is no inclination beyond this radius, where ϖ is the galactocentric distance.

(ii) *Cross Section of Inner Spiral Arms*

In order to examine whether the radio continuum spurs are really associated

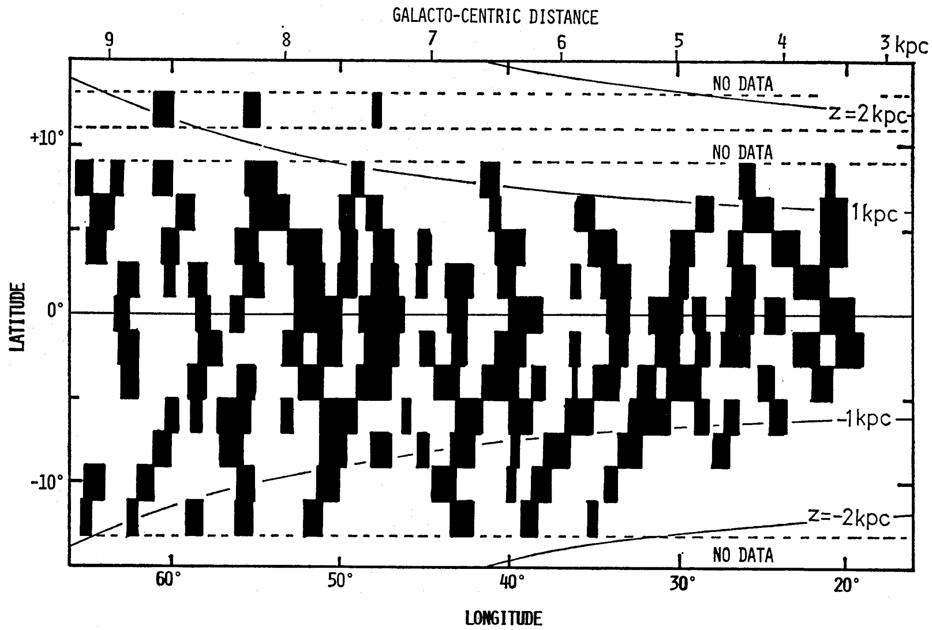

Fig. 4. Cross sections of inner spiral arms of H I gas cut along a locus of maximum radial velocity as seen from the sun and projected onto the (l, b)-plane. Width of each filled square indicates the spread in longitude. Indicated with thin lines are the height z from the galactic plane. The galactocentric distance ϖ is also indicated at the top of the figure. Note that the inner arms can be continuously traced up to $|z|=1$ kpc and more, and that the z-extensions of the H I arms are systematically inclined toward the anticenter sides.

with the inner spiral arms, we search for some H I-gas features apparently associated with them. For this purpose, we inspect the distribution of H I gas located near the points tangential to galactic circular rotation, or the gas around a locus of maximum radial velocity.

We read the positions of the maxima of H I-gas density on observed longitude-radial velocity $(l\text{-}v)$ diagrams along a locus corresponding to the usual rotation curve (e.g., KERR 1964). We use the observed $(l\text{-}v)$ diagrams presented by BURTON (1970) and BURTON and VERSCHUUR (1973) at every 2° between $b=-12°$ to $+12°$. We then plot the positions of maxima of H I density on the (l, b)-plane as shown in figure 4, where the width of each filled square indicates approximate spread in longitude of the arm or a condensation at the tangential velocity. Also indicated are galactocentric distance ϖ and height z from the galactic plane. This figure shows just the cross sections of the inner spiral arms of H I gas cut along the locus of the maximum velocity as seen tangential to galactic rotation.

Remarkable in this figure is the fact that the inner arms are not confined within the usual gaseous disk of thickness of 100 pc, but can be traced up to $b=\pm 10°$ and more. This implies that the arm gas extends up to $z=\pm 1$ kpc or more as in the distant outer arms (KEPNER 1970), although the density is very low at this height. For example, the Sagittarius arm at $(l, b)\cong(50°, 0°)$ can be continuously traced at least up to $b=10°$ above the galactic plane, and down to $b=-12°$ below the plane. Similar features are also observed for the Scutum arm and other inner arms.

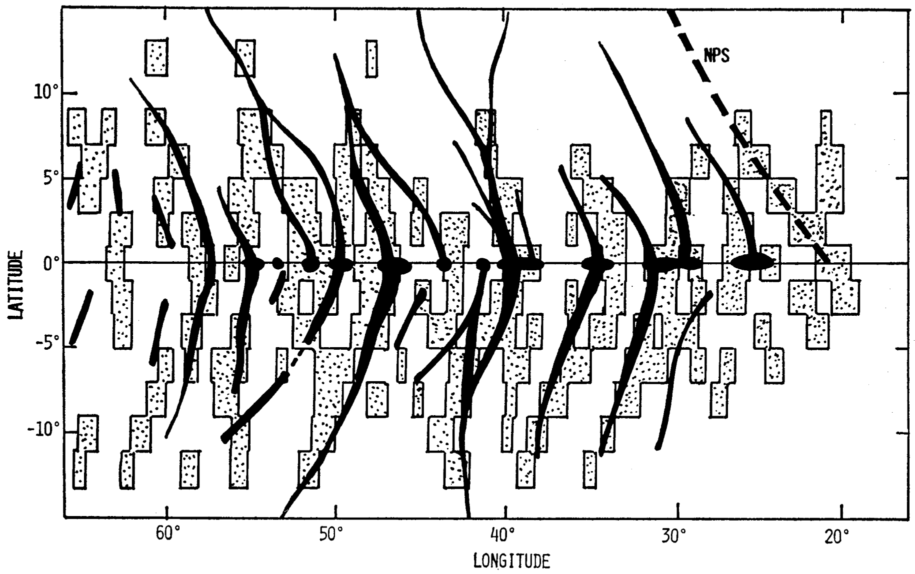

Fig. 5. Superposition of the continuum-spur ridges at 408 MHz and H I ridges of the inner-arm cross sections. Both ridges coincide with each other in their positions and inclinations. The continuum ridges have been collected from HASLAM et al. (1974) (see SOFUE 1976).

In addition, we notice that these z-extensions systematically incline toward the anticenter sides roughly at a constant angle in a way similar to the radio spurs. Such a systematic inclination is clearly recognized for the arm at $(l, b) = (34°, 0)$ which extends to $(39°, -12°)$ and for the arms near this direction. Figure 5 shows a superposition of the observed ridges of the continuum spurs and the H I ridges of the cross sections of the arms. Most of the H I ridges coincide with the continuum ridges in the position and in the tilt angle. These facts indicate a positional association of the spurs and the vertical extension of H I gases at the inner spiral arms, and support our GS hypothesis for the origin of the inner spurs.

The H I-gas extension observed above the inner spiral arms is in good agreement with the idea of "H I banks" extending up to $z = 1$-2 kpc above the Perseus arm and outer arms (KEPNER 1970). Correlation between the H I and continuum ridges is also in agreement with our findings that the H I gas extends above the Perseus arm in rising and falling motion and is associated with an enhancement of radio emission or the "Perseus hump" in the continuum background (TOSA and SOFUE 1974; SOFUE and TOSA 1974).

3. *Origin of the Spur Inclination*

We try to interpret the observed inclinations of continuum ridges and the H I cross sections of the inner spiral arms. In our GS hypothesis, the spurs are attributed to the nonthermal banks located above the spiral arms. They are considered to be produced by inflation of magnetic fields with cosmic rays as a result of the Parker-type instability (Paper I). The inflation is enhanced above the galactic shock regions.

Unless some radial force acts on the spurs, the inflation should take place exactly in the z-direction. Then the spur ridges at $l \leqq 50°$ should likewise appear perpendicular to the galactic plane as seen on the model map in figure 4. Hence, the systematic features of the spurs trailing toward the anticenter sides can conceivably be regarded as evidence for the existence of some radial force to push the banks outward. The force is acting solely within ~ 7 kpc of the galactic center.

Three candidates for the horizontal force can be considered: One is that it is due to a wind in the halo blowing horizontally from the central region of the Galaxy. A second candidate is radiation pressure of starlight on dust grains involved in the banks. A third is that the inclination is intrinsic to the formation of the spurs due to the three-dimensional galactic shocks.

(i) *Horizontal Stream of Gas in the Halo*

(a) *Static model.* We begin with the case that the radio spurs are in a static equilibrium state. We assume that in this case the inflated magnetic lines of force are fixed on the galactic disk at their roots, and in a static equilibrium state: their tension is balanced with the cosmic ray pressure. When a stream blows radially from the center and hits the nonthermal banks, their upper portions may be trailed leeward, or away from the galactic center, by the dynamical pressure.

Let V designate the wind velocity, ρ the density of gas in the stream, B_0 the magnetic field strength in the spur when there acts no radial force, and B_1 that when it is distorted by the stream. Then the fields B_0 and B_1 can be approximately related to the dynamical pressure as

$$(B_1^2 - B_0^2)/4\pi \approx \rho V^2 \ . \quad (1)$$

The field strength B_1 is related to B_0 as $B_1 \approx B_0/\cos i$, where i is the tilt angle of the spurs. Consequently we have

$$(B_1^2/4\pi) \sin^2 i \approx \rho V^2 \ . \quad (2)$$

As evaluated in Paper III, the field strength in the spur is about $B_1 \cong 2\times 10^{-6}$ G. Substitution of this value and the mean tilt angle $i \cong 25°$ into equation (2) yields $\rho V^2 \cong 6\times 10^{-14}$ dyn cm^{-2}. If the gas density of the wind is 10^{-3} H atoms cm^{-3} (SPITZER 1954; TOSA and SOFUE 1974), we obtain the wind velocity as $V=62$ km s^{-1}.

(b) *Blob model.* Next we consider the case that the spurs are composed of independent magnetic blobs with gas and cosmic rays which are ejected out of the spiral arms as a result of the nonlinear inflation. TOSA and SOFUE (1974) and SOFUE and TOSA (1974) have shown the existence of rising and falling motion of gas above the Perseus and the outer spiral arms. They have shown that the gas clouds are ejected vertically out of the arms with an initial velocity of about 70 km s^{-1} in the z-direction. The gas clouds fly almost freely through the halo and attain a maximum height of z=1-2 kpc. They fall back again into the disk after some 10^7-yr flight. The H I-gas density ρ_0 in the clouds has been observed to be 10^{-2} atoms cm^{-3} (KEPNER 1970) for the outer arms.

If this mechanism applies to the inner spiral arms, and the radial gas stream blows against the blobs (or clouds), their trajectories must be drifted horizontally in the anticenter direction. Equations of motion of the cloud are written as follows:

$$\frac{d^2z}{dt^2}=-K_z\ , \tag{3}$$

$$\frac{d^2\delta\varpi}{dt^2}=\left(\frac{\rho S}{\rho_0 W}\right)V^2+\frac{h^2}{\varpi^3}-K_{\varpi}\ , \tag{4}$$

and

$$\varpi^2\frac{d\psi}{dt}=h=\text{constant}\ . \tag{5}$$

Here $\delta\varpi$ is the displacement in the galactocentric distance ϖ, ψ the angle around the rotation axis, K_z the z-component of the gravitational acceleration, K_{ϖ} its radial component, and S and W are the cross section and volume of the blob, respectively. When the blob size is constant throughout the flight, equation (4) can be integrated to give

$$\delta\varpi=-\frac{1}{n^2}\left(\frac{\rho S}{\rho_0 \varpi}\right)V^2(\cos nt-1)\ , \tag{6}$$

where n is the epicyclic frequency at ϖ and is given by

$$n=\left[\left(\frac{\partial K_{\varpi}}{\partial\varpi}\right)_{\varpi}+\frac{3h^2}{\varpi^4}\right]^{1/2}\ . \tag{7}$$

If the displacement is small enough, we have

$$\delta\varpi\approx\frac{1}{2}\left(\frac{\rho S}{\rho_0 W}\right)V^2t^2\ . \tag{8}$$

If the blob is assumed to be a sphere of radius R, the tilt angle is approximately related to the above quantities as

$$\tan i\approx\frac{\delta\varpi}{Z}=\frac{3\rho}{8\rho_0 ZR}V^2{t_{\rm m}}^2\ , \tag{9}$$

where $t_{\rm m}$ is the time taken for the cloud to reach its maximum height Z, namely, $t_{\rm m}=\int_0^Z dz/v_z$, and is obtained through a numerical integration of equation (3).

We adopt $Z=1$ kpc and $t_{\rm m}=2\times10^7$ yr for the inner spurs, and also assume $R=200$ pc as a typical blob size. Substitution of these values and $i\cong25°$ into the above equations leads to $\rho V^2\cong1\times10^{-13}$ dyn cm^{-2}. If we take again that $\rho\approx10^{-3}$ atoms cm^{-3}, we have $V\cong80$ km s^{-1}, close to the velocity estimated from the static field model in subsection (a).

(ii) *Radiation Pressure*

CHIAO and WICKRAMASINGHE (1972) have stressed the importance of radiation pressure of the starlight field in accelerating interstellar dust grains in the z-direction. They also showed that the radiation pressure can assist development of the Parker-type instability. Combining their idea with our model for the spur formation, we can expect that a considerable amount of dust grains is involved in the nonthermal banks or blobs above the spiral arms (SOFUE and TOSA 1974). Once the dust grains rise up into the halo out of the dusty gaseous disk, they will be directly exposed to strong radiation from the whole of the Galactic system, especially from the central bulge.

We examine whether the radiation pressure could push the spurs so strongly that they are tilted by 20° or so. Outside the gaseous disk, the absorption of starlight will be small and the radiation field at high z-region would be of the order $u_r = L/2c(4\pi\varpi^2)$, where L is the total luminosity of the Galaxy within a galactocentric distance ϖ. The radiation pressure p_r on the spur with a thickness D is evaluated as

$$p_r = \frac{1}{3} u_r \left[1 - \exp\left(-\frac{\rho_0}{\rho_{\rm disk}} \kappa D\right)\right] \approx \frac{1}{3} u_r \frac{\rho_0}{\rho_{\rm disk}} \kappa D\,, \tag{10}$$

where $\rho_{\rm disk}$ and κ are, respectively, the gas density and absorption coefficient of the starlight in the normal gaseous disk. We have here neglected the drift motion of the grains through the gas, inclusion of which will somewhat reduce the pressure. The above equation should be therefore regarded as giving an upper value.

If we take, typically, $L = 10^{44}\,{\rm erg\,s^{-1}}$, $\varpi \approx 6\,{\rm kpc}$, $\rho_0/\rho_{\rm disk} \cong 10^{-2}$, $\kappa \approx 1\,{\rm mag\,kpc^{-1}}$, and $D \cong 200\,{\rm pc}$, then we obtain $p_r \approx 2\times10^{-16}\,{\rm dyn\,cm^{-2}}$. We have assumed that the grain abundance per unit mass in the spur region is the same as in the disk. This value is three orders of magnitude smaller than the magnetic energy density $B_0^2/8\pi$ and the kinetic energy density of the blob motion $\rho v_z^2/2$.

(iii) *Galactic Shock Origin*

A fully three-dimensional structure of the galactic shock waves has not been worked out yet (see TOSA 1973). We here make a conjecture for the form of the shock front in relation to the inclination of the spurs.

We consider that the shock is formed in the galactic plane along the spiral arm responding to the spiral gravitational potential of the density waves. The disturbance is propagated through the gas in the disk and also in the z-direction with sound speed, resulting in a shock front not perpendicular to the plane but inclined downstream above and below the plane. The situation is analogous to a bow shock formed by an obstacle in a supersonic gas flow. The angle χ between the front and the galactic plane is roughly the Mach angle: $\sin\chi = 1/M = c_s/v_p$, where M is the Mach number, c_s the effective sound speed, and v_p the component of the gas velocity normal to the spiral pattern.

For the trailing spiral arm, the gas passes through the shock from the galactic center side to the anticenter side. The shock front is always inclined toward the anticenter side.

Since the spur is considered to be a result of the tangential view of a radio-emitting bank along the shock front, the spur inclination is related to the Mach angle as $i = 90° - \chi$. For $c_s = 10\,{\rm km\,s^{-1}}$ and $v_p = 20$-$30\,{\rm km\,s^{-1}}$, we have $i = 60$-$70°$. Since the effective sound velocity increases with z at the high z-region, the inclination decreases with z or the shock surface becomes concave toward the anticenter side. However, we should remember that the shock itself would be weakened, to disappear at higher z-regions where the effective sound velocity is thought to exceed the gas velocity v_p.

In conclusion, the sense of the inclination and the configuration is qualitatively compatible with some of the spurs, but the angle $i = 60$-$70°$ is too large compared with the observed ones, 20-30°.

From these considerations, we may conclude that, insofar as the GS hypothesis is taken, the inclination can be naturally accounted for in terms of dynamical pressure of the order of $\rho V^2 = 10^{-13}$ dyn cm^{-3} in the horizontal direction. This yields a radial velocity of 60-80 km s^{-1}, if the stream density is assumed as 10^{-3} H atoms cm^{-3}. From the present discussion alone, we cannot decide which is the case, the static or the blob model. Of course a possibility remains that the spurs are composed both of the blobs and static fields. It is interesting to note that in both cases, roughly the same wind velocity is obtained.

We must keep in mind that the stream blows only in the inner region of the Galaxy. In the space above the Perseus and the outer arms, no significant drag force or horizontal force is observed from the analysis of H I gas motion (TOSA and SOFUE 1974; SOFUE and TOSA 1974).

4. *Origin of the Horizontal Stream*

We discuss the origin and some physical problems concerning the horizontal stream introduced in the preceding section.

(a) *Galactic wind.* No promising theory seems to have been proposed yet for the gas dynamics in our galactic halo (WOLTJER 1965). BURKE (1968), JOHNSON and AXFORD (1971), and MATHEWS and BAKER (1971) have worked out a galactic wind in spherically symmetric elliptical galaxies and stellar systems. It is unclear whether our horizontal stream is a phenomenon similar to the galactic wind.

JOHNSON and AXFORD (1971) have suggested that, although our Galaxy exhibits a highly flattened geometry, this may not be crucial if the dynamics is dominated by the more symmetric inner region (i.e., within $\sim$4 kpc) of the Galaxy. They have considered that an expanding galactic corona is likely to be a natural consequence of the galactic wind theory for any galaxy, including our own. Unfortunately, no quantitative treatment has been worked out yet of the wind in our galactic corona.

We now make some comments on the nature of our stream, when it is assumed to be of the galactic-wind origin. We have thus far paid attention to the radial component of the stream alone. If the stream comes from the central region of the Galaxy or the central bulge, an angular momentum problem cannot be left untouched: the conservation of the angular momentum inevitably yields a velocity component tangential to the galactic rotation when referred to the rotating disk. As a result the stream direction has a component parallel to the spiral arms. The tangential component will amount to 200-250 km s^{-1} at 5-10 kpc from the galactic center, provided the friction between the stream and the disk matter is neglected.

The tangential component will cause the spurs to bow leeward parallel to the arms in addition to the radial tilt. However, it seems still difficult to separate this tangential inclination only from the observed inclinations of the spurs.

(b) *von Kármán's solution.* We suggest an alternative mechanism to cause a large-scale gas flow in the halo. Suppose that the gaseous disk is a thin rigid disk with a sufficiently large diameter and is rotating at an angular velocity Ω, and that the halo gas is uniformly distributed without source or sink. When friction between the gas and the disk is taken into account, von Kármán's solution could be applied to the gas close to the disk in the halo. The flow velocity in a rest frame of reference is

$$u_{\varpi} = \varpi \Omega F(z) , \quad u_{\phi} = \varpi \Omega G(z) , \quad u_z = (\mu \Omega)^{1/2} H(z) , \tag{11}$$

(e.g., LANDAU and LIFSHITZ 1959). Here, u_{ϖ}, u_{ϕ}, and u_z are the radial, tangential, and z-directional components of the flow velocity, respectively, μ is the kinematical viscosity, and F, G, and H are numerically given as functions of z.

We can take $(\mu/\Omega)^{1/2} \approx (\sigma\tilde{\omega}d/V_{\phi})^{1/2} \approx 1$ kpc, with $\sigma \approx 30\,\mathrm{km\,s^{-1}}$, $d \approx 1$ kpc, $\varpi \approx 5$ kpc, and $V_{\phi} \approx 250\,\mathrm{km\,s^{-1}}$, where σ is a typical velocity of random motion of gas in the halo, d a typical scale of variation of the velocity, and V_{ϕ} the rotational velocity of the galactic disk at ϖ. Making use of the numerical values for F, G, and H (LANDAU and LIFSHITZ 1959), we obtain $u_{\varpi} = 50\,\mathrm{km\,s^{-1}}$, $u_{\phi} = 130\,\mathrm{km\,s^{-1}}$, and $u_z = -60\,\mathrm{km\,s^{-1}}$ at $z = 1$ kpc. Similarly, we have $u_{\varpi} = 45\,\mathrm{km\,s^{-1}}$, $u_{\phi} = 175\,\mathrm{km\,s^{-1}}$, and $u_z = -22\,\mathrm{km\,s^{-1}}$ at $z = 500$ pc. When the velocity is referred to the rotating disk, the tangential velocity u_{ϕ} leads to a relative velocity to the disk as $u_{\phi} - V_{\phi} \approx -120\,\mathrm{km\,s^{-1}}$ at $z = 1$ kpc, and $-75\,\mathrm{km\,s^{-1}}$ at 0.5 kpc.

The radial velocity here obtained is comparable to that required for the spur inclination in section 3. We should notice that a negative z-velocity arises: the stream blows down toward the galactic plane with $u_z = -60\,\mathrm{km\,s^{-1}}$ at $z = 1$ kpc, and with $-22\,\mathrm{km\,s^{-1}}$ at $z = 500$ pc. Such a z-motion would be also difficult to detect in the present analysis of the spurs. An analysis of intermediate-velocity clouds of H I gas at high latitudes (TAKAKUBO 1967) might be useful to learn about such a large-scale z-motion.

We must remember that the analysis of the spur inclination shows the existence of radial dynamical pressure acting only in the inner region ($\varpi \lesssim 7$ kpc). This fact implies that von Kármán's solution applies to the inner region, but not entirely in the Galaxy.

5. *Conclusions*

A detailed inspection of inner galactic spurs in the radio continuum has revealed a systematic inclination of their ridges toward the anticenter sides at roughly a constant angle of 20-30°. The inclination has been interpreted in terms of the tilted configuration of the bank-shaped emitting regions of nonthermal radio waves. The nonthermal banks are located above the inner spiral arms. In order to produce the observed spur inclination, the nonthermal banks should be tilted by 20-30° from the perpendicular. The inner spurs are shown to be associated with z-extensions of H I gas emerging from the inner spiral arms. The H I extensions are also tilted in coincidence with the nonthermal spurs.

The spur inclination may be due to a horizontal dynamical pressure on the gas and magnetic field when the spurs are blown by a horizontal gas stream of galactic scale. The dynamical pressure is estimated to be of the order of 10^{-13} dyn $\mathrm{cm^{-2}}$. The stream velocity is 60-80 $\mathrm{km\,s^{-1}}$, if the density is taken as 10^{-3} H atoms $\mathrm{cm^{-3}}$. As the cause of the stream, we have suggested two candidates: the galactic wind originated from the central bulge of the Galaxy, and the steady outward flow of the halo gas driven by the interaction between the halo and the disk.

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